

COLLIDING HIGH BRIGHTNESS BEAMS IN THE LHC

T. Pieloni, X. Buffat, W. Herr, R. Giachino, E. Metral, G. Papotti, CERN, Geneva, Switzerland

Abstract

The CERN-LHC is a high energy particle collider, where intense proton bunches are brought into collision. In order to achieve optimum performance, the bunches must have a high brightness, leading to strong and significant beam-beam effects. Experimental tests during the first two years of its operation have shown that beams with very high brightness can be collided head-on without detrimental effects on the beam dynamics. Such head-on collisions are therefore not expected to limit the LHC performance. Long range beam-beam interactions dominate the adverse effects on the dynamics but can profit from an increased beam brightness, in particular from small emittances. We summarize the experimental results and compare with the theoretical expectations. This allows to optimize the performance for future operation and a definition of promising upgrade scenarios.

LHC HIGH BRIGHTNESS BEAMS

To deliver the record luminosities achieved this year the Large Hadron Collider injector chain potential for brightness has been exploited during this first part of 2012 physics run. The injector chain has been optimized and can provide the LHC with brighter than nominal beams as already shown in 2011 run. In 2012 run intensities up to $\approx 1.7 \times 10^{11}$ protons per bunch have been delivered and have become operational, to be compared with the 1.15×10^{11} ppb in the Design Report [1], for emittances of $\approx 2 \mu\text{m}$ ($3.5 \mu\text{m}$ for nominal LHC parameters). This parameters have been achieved operationally for 50 ns bunch spaced beams. During machine development experiments the beam brightness has been pushed even further colliding single bunches with intensity of $\approx 3.1 \times 10^{11}$ ppb and transverse emittances of less than $2 \mu\text{m}$. With such high brightness beams of course beam-beam effects are pushed to the limits and a careful understanding of the different effects define the optimum choice of parameters to improve performances for the 2012 physics run, for the 7 TeV run and some guidelines for possible upgrade scenarios.

BEAM-BEAM EFFECTS IN THE LHC

The LHC layout is shown in Fig. 1. The two proton beams collide with a finite crossing angle at four Interaction Regions (IR) where they share a common beam pipe. At the experimental crossing the beams experience head-on collisions in CMS and ATLAS while they collide with a finite offset at LHCb. Several long range interactions are experienced on both sides of the four experiments. During the 2012 run, beams up to 1380 bunches spaced by 50 ns are used. This configuration gives variable number of

long range encounters between 30 and 74 maximum (much lower number compared to the nominal 40-120 encounters with a 25 ns beam) depending on the bunch position in the filling scheme.

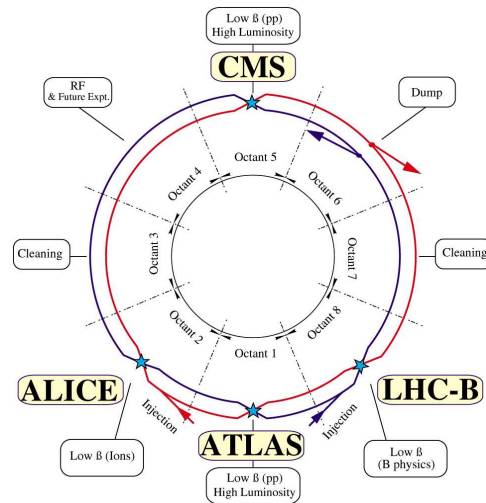


Figure 1: LHC layout.

HEAD-ON COLLISIONS

Due to the beam filling schemes and the geometry of the different Interaction Points (IPs) the bunches can be classified in different families depending on the number of head-on collisions as well on the number of parasitic long range encounters. The major contribution to beam losses in collision comes from the head-on collisions. For the 2012 run this results in bunch by bunch relative losses as visible in Fig. 2. The red lines in Fig. 2 corresponds to bunches colliding only in LHCb with a transverse offset which cannot be considered as head-on collision as also evident from the small fraction of the losses from this IP. Real head-on collisions occur in ATLAS and CMS from which the biggest contribution to losses come (green lines in Fig. 2). The collision with 4σ in LHCb adds up to the losses for bunches colliding in ATLAS, CMS and LHCb (blue lines in Fig. 2).

Head-on Beam-beam Tune Shift

During 2011 experiments it has been proved that a tune shift of 0.017 per IP can be achieved with single bunch with no evident deterioration of beam parameters neither any dynamics effect [2]. The experiment carried out in 2011 represents still the maximum tune shift reached with very high brightness beams in the LHC. During the 2012 run during regular operation we have tune shift from head-on collisions of ≈ 0.008 per IP, leading to a total tune shift of the order of ≈ 0.02 in total.

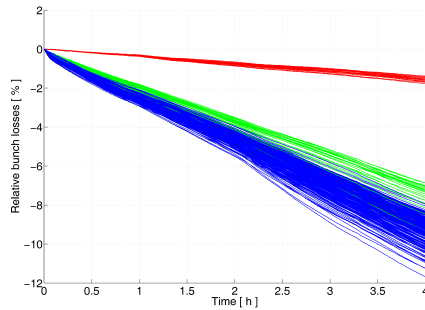


Figure 2: Losses in relative percentages for different bunch head-on families. Red line corresponds to bunches colliding only in LHCb, green to those colliding in ATLAS and CMS while blue line to bunches colliding in ATLAS, CMS and LHCb.

Figure 3 is the spectrogram of the vertical plane of beam 1 during a dedicated experiment. A maximum tune change from 0.32 to 0.30 is achieved in the vertical plane when going into collision in IP1 and IP5. In Fig. 3 also the effects of offset collisions are visible as sharpe steps in tune shift. Detailed analysis of this case can be found in [3].

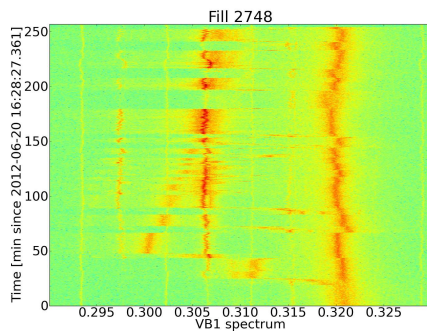


Figure 3: Spectrogram during the β^* leveling experiment.

In Table 1 a summary of the beam parameters reached over the last two years are compared to the nominal beams properties.

Table 1: LHC Parameter Reach in 2011 and 2012

Parameter	Nominal	2011	2012
Intensity (ppb)	1.15 mm	2.3×10^{11}	3.1×10^{11}
Emittances	$3.75 \mu m$	$\leq 2.0 \mu m$	$\leq 2.0 \mu m$
β^*	0.55 m	1.0 m	0.6 m
ξ/IP	0.0035	0.017	0.01
Bunch spacing	25 ns	50 ns	50 ns
Bunches/beam	2808	1380	1380

Coherent Beam-beam Modes

Coherent beam-beam modes have been observed in several experiments when few bunches are collided. Also

during dedicated single bunch experiments coherent beam-beam modes have been measured and no detrimental effect has been associated to their appearances. Figure 4 shows analysis, as defined in [2], of the sum and difference signals of the two bunches while colliding and shows the two σ and π mode frequencies for the horizontal plane. The picture shows that the two signals are out of phase, when the σ mode frequency is maximum the π mode in minimum and viceversa.

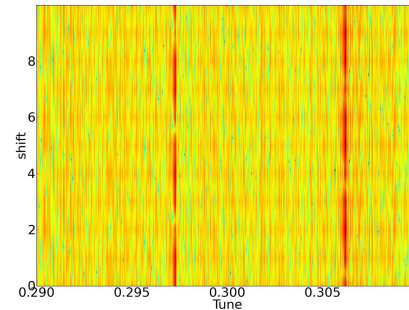


Figure 4: Coherent mode frequencies in the LHC.

LONG RANGE INTERACTIONS

During regular operation long range encounters are kept as weak as possible to preserve the beam qualities to ensure the maximum integrated luminosity per fill. This is possible by keeping emittance as small as possible and sufficient separation at the parasitic encounters by a large enough crossing angle. Since the IR settings (crossing angle, beta*, transverse emittance) depends strongly on the effects of these interactions several experiments were foreseen performed to define the limits expected from the long range beam-beam effects [4]. In 2012 two experiments were performed considering long range collisions only from IP1 and IP5. The aim of the experiments was to define the effects of intensity and of β^* since different from 2011 operation. The motivation for this study was to define an optimum set of beam parameters for the 50 ns beams and to compare to previous studies to test analytical scaling laws [5]. The experiment consists of reducing the vertical crossing angle in IP1 and observing and monitoring losses and bunch emittances. Figure 5 shows the bunch by bunch losses for the different half crossing angles. Initial intensities were of 1.6×10^{11} p/bunch and bunches along the train were experiencing from 16 to 32 long range encounters per turn. First losses are observed at a half crossing angle of $\approx 96 \mu rad$, corresponding to a separation of around 6σ at IP1. Losses are more pronounced for bunches with larger number of long range and almost negligible for the others.

The second part of the experiment was to reduce in the same way the horizontal crossing angle in IP5. The losses for the second part of the experiment are shown in Fig. 6. The picture shows that bunch to bunch differences are less pronounced and that important losses start at a smaller half

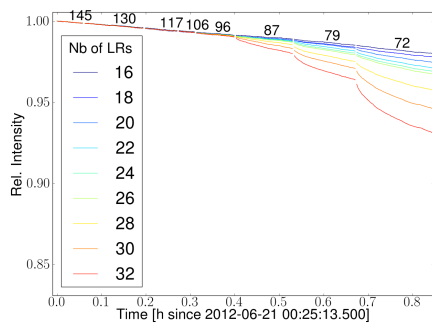


Figure 5: Single bunch losses in beam 1 in time for different crossing angle at IP1.

crossing angle of $\approx 50 \mu\text{rad}$ corresponding roughly to $3.5 - 4 \sigma$ separation. Bunches seems affected more equally when the two crossing angles are equalized but on different planes. This is an evidence of the passive compensation of PACMAN effects with the alternation crossing of IP1 and IP5. More details can be found in [6].

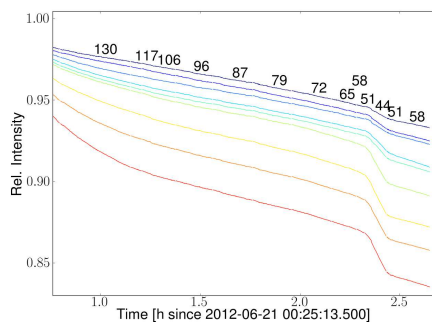


Figure 6: Single bunch losses in beam 1 in time for different crossing angle at IP5.

Pacman Effects

From the experiment performed we can also visualize the Pacman effects shown in Fig. 7 left where the bunch by bunch integrated losses are plotted as a function of the position of the bunch in the train. It is evident that the losses depends strongly on the number of long range encounters the bunches undergo which are represented in Fig. 7 right. From Fig. 7 right it is clear that bunches with less long range will have smaller losses while those with maximum number of 16 have much larger losses (of about 12 – 13%). To be noticed that the first 12 bunches of the train were not colliding and therefore do not show any significant effect.

SUMMARY

The different beam-beam effects experienced during the last year operation and special experiments have been presented and are summarized as:

- Beam-beam head-on and long range effects are clearly visible in the beam dynamics

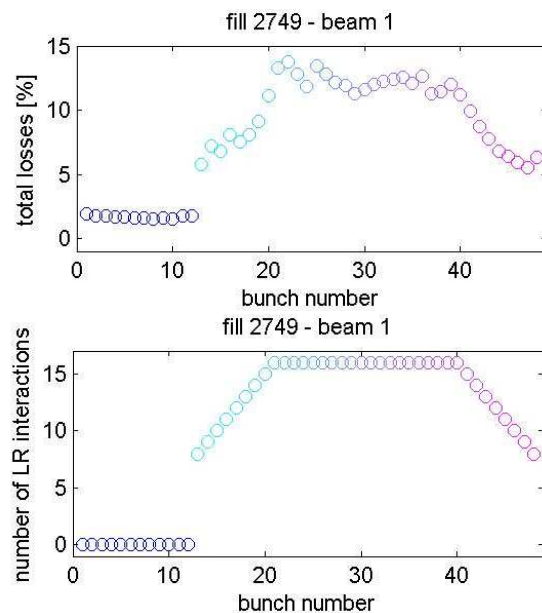


Figure 7: Integrated bunch by bunch losses (left) and number of long range encounter (right) along the bunch train.

- Larger than nominal tune shifts are confirmed in standard operation
- The study of long-range encounters on beam lifetime and losses is proved for different sets of parameters
- Beam lifetimes and losses strongly depend on bunch families Pacman and Super Pacman

More recent observations of beam-beam effects confirm the 2011 findings. Several studies to explore new beam parameters have been addressd and scaling laws for 7 TeV are under study.

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